# 2005 Annual Project Summary Integrating geologic, paleoseismic, and geodetic data using a Bayesian modeling approach to constrain fault-zone and lower-crustal rheology along the southern San Andreas Fault, CA

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## Investigations Undertaken

This project improves estimates of earthquake hazard potential in Southern California by (1) formally assimilating geologic, geodetic, seismic, and paleoseismic data into a statistical framework that refines knowledge of the timing and recurrence of ancient earthquakes, slip rates and locking depths of active faults, and relaxation time of a viscoelastic plastosphere, and (2) applying these methods to data collected within and around active faults in Southern California. The parameters, and their uncertainties inferred and/or refined by our methods, serve as important inputs to the evaluation of seismic hazards. Specifically, this project uses geologic, seismologic, and paleoseismic data as a priori knowledge in a Bayesian model that relates lower crustal properties to deformation observed geodetically during the earthquake cycle. By comparing the modeled deformation to those observed, the Bayesian approach statistically evaluates the sets of a priori estimates that are more likely to generate the geodetic data observed, and thus initial estimates of lower crustal properties may be improved. In other words, by considering all of the data together in a Bayesian framework, we achieve a far more precise estimate of the fault zone and lower crustal properties than if each type of data is considered in isolation. We have chosen to apply our methodology to the fault systems of Southern California because: (1) These structures pose significant seismic hazards; (2) Deformation in the area may be characterized by recurring seismic slip and postseismic viscoelastic relaxation; and, (3) Seismologic, geologic, paleoseismic, and geodetic data sets are publicly available.

# Results

We have constructed three different 2D models of infinitely long strike-slip faults in order to use geologic and geodetic data to estimate the rheology of the lithosphere in southern California. Each of these models are extensions of the original Savage-Prescott viscoelastic periodic cycle models involving an elastic plate overlying a Maxwell viscoelastic half-space. We refer to these extended models as "episodic" earthquake cycle model models because the earthquakes are imposed at specified times and do not necessarily occur at a regular recurrence interval.

The simplest model is what we call the modified Savage-Prescott model. Slip on a vertical fault is modeled in an elastic plate overlying a viscoelastic half-space. Earthquakes occur with the same slip magnitude at a regular interval from time negative infinity up to a certain point of time in the past. After this point in time, individual earthquakes are applied at specified times and specified slip magnitudes. The timing of the most recent earthquakes is determined from the paleoseismic and historic records.

We have found that the lithosphere rheology is best resolved with data spanning a wide interval of time. To include data from as many time periods as possible, we have used GPS data for contemporary deformation measurements, triangulation data that records deformation back to about 1930, and postseismic GPS time-series data from the 1992 Landers earthquake. This gives deformation measurements that span the second half of an earthquake cycle (triangulation and GPS data) as well as the rapid deformation period immediately after an earthquake (Landers data). We obtained all the historical triangulation data for the region from the National Geodetic Survey and have calculated the average shear strain rate across the Mojave section of the San Andreas Fault (SAF) at different time intervals.

We inverted this data using the modified Savage-Prescott model to obtain estimates of fault slip rate and lithosphere rheology. We used paleoseismic probability distributions on timing of past earthquakes (Hilley and Young [in press]) as prior information in a Bayesian inversion. Figure 1 shows the posterior distributions on these parameters and figure 2 shows the fit to the three sets of geodetic data.

It is interesting to note that if we don't use the post-Landers data, the inversion places no upper bound on the average plastosphere viscosity. The Landers data are not fit by relatively high viscosities and places an upper bound on this parameter.

One problematic result is that the plastosphere viscosity is greater than $10^{19}$ Pa s while numerous independent estimates of upper mantle viscosity from rebound studies of ancient lakes shows that the viscosity of the upper mantle beneath the western US is no more than $10^{19}$ Pa s. We therefore investigated a layered viscoelastic model.

The layered viscoelastic episodic earthquake cycle model is constructed exactly the same way as the modified Savage-Prescott model, except the plastosphere is modeled with three viscoelastic layers representing the lower crust, uppermost mantle, and mantle. We perform exactly the same inversion as above using this model. The resulting viscosity structure is shown in Figure 3. The posterior distributions on the viscosity of each layer are superimposed on theoretical viscosity profiles constructed from laboratory creep measurements in Figure 3. The model suggests a relatively highly viscous lower crust and uppermost mantle overlying a less viscous mantle. This result reconciles the discrepancy between the lake unloading studies and our first inversion.

Finally, we have begun constructing 2D boundary element models (BEM) of strike-slip faults that incorporate lateral variations in lithosphere rheology. We will apply these models to the Salton Sea area of the San Andreas fault system where heat flow and seismic data suggest significant lateral variations in crustal properties. The BEM formulation is illustrated in Figure 4. We use the displacement discontinuity method to bond regions with different elastic and viscoelastic properties together. We idealize the earth as an elastic lithosphere overlying a viscoelastic asthenosphere. The elastic lithosphere is forced at the ends at a constant velocity. The fault in the lithosphere is locked between earthquakes down to a specified depth and creeps below this locking depth at constant resistive stress. Earthquakes are imposed on the fault above the locking depth as sudden discontinuities at specified times such that the long-term slip rate on the fault is the same as the imposed far-field plate velocity. The separate solutions for a dislocation in an elastic half-space and in a viscoelastic half-space are used to discretize the boundaries of the elastic and viscoelastic media. The two media are bonded by matching displacements and stresses at coinciding dislocations. The numerical step in this boundary element formulation involves solving a system of equations that relates the specified stress and displacement boundary conditions to the distribution of dislocation magnitudes on all the elements.

Figure 4B shows the effect of variable elastic thickness and lateral variations in elastic stiffness across the fault on surface velocities. In this case the fault slips 30 mm/yr with periodic earthquakes every 200 years. The viscosity of the asthenosphere is $10^{19}$ Pa s. Not surprisingly, the lateral variations in lithosphere properties introduces asymmetry to the surface velocity pattern and the effect can be significant.

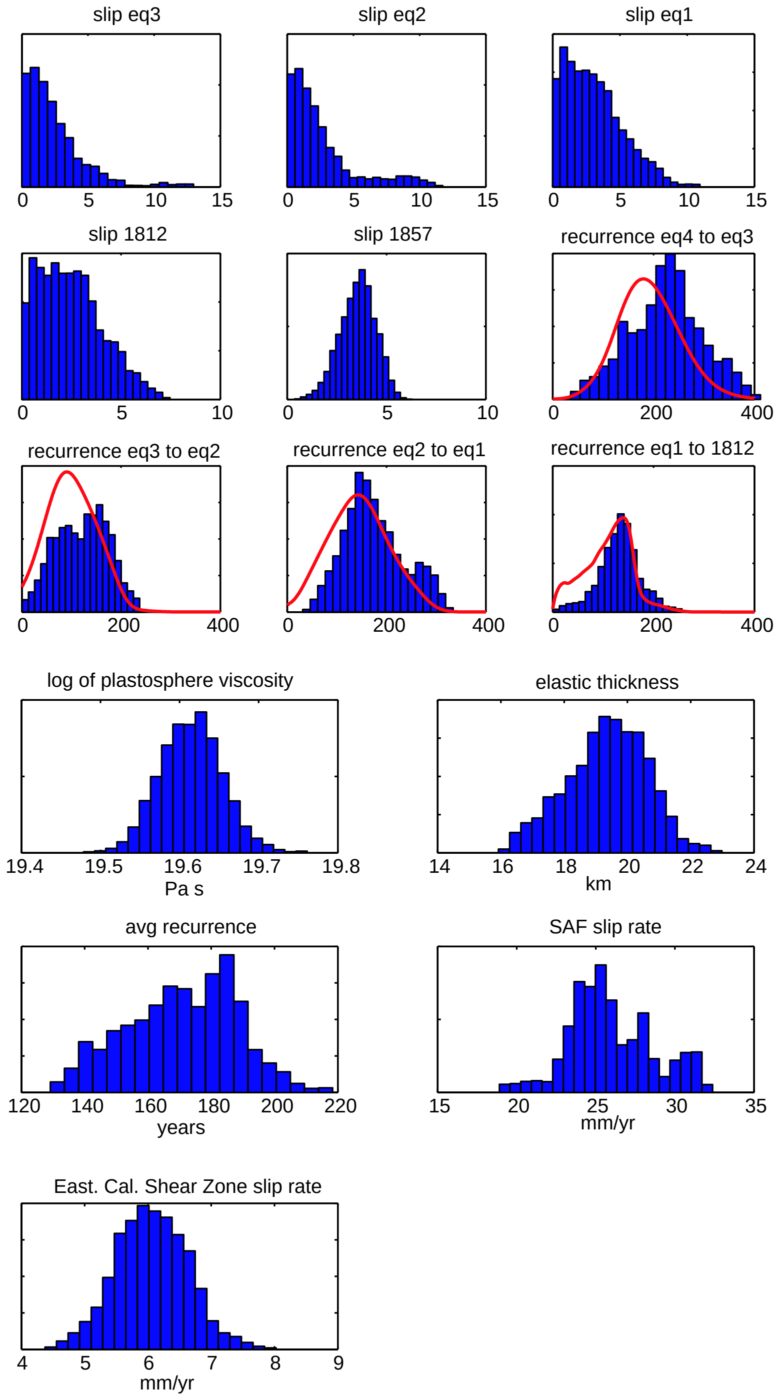


Figure 1: Posterior distributions from inversion of geodetic data using the modified Savage-Prescott model. Slip during each earthquake is in meters and recurrence times in years. The red curves show a priori recurrence time probability distributions from paleoseismic data.

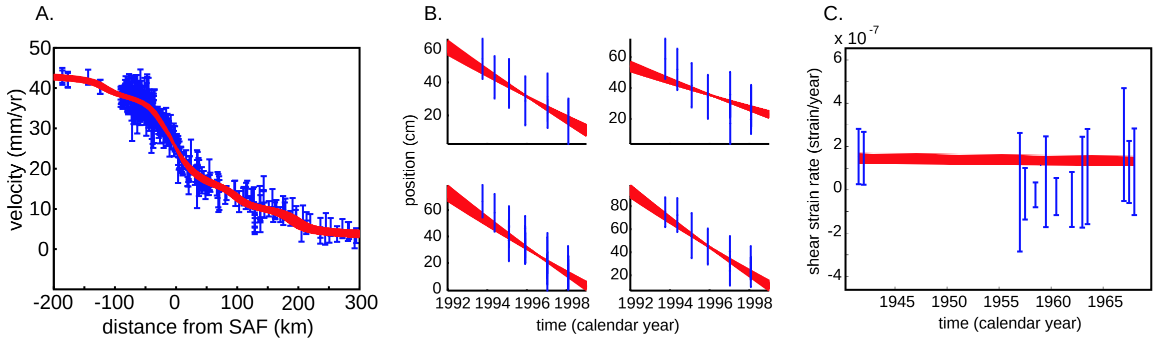


Figure 2: A. GPS data across the Mojave Desert region. Red curves show posterior distribution of modeled velocities. B. Some of the GPS time series data following the Landers earthquake. Red curves show posterior distribution of modeled time-series. C. Strain-rate measurements across the San Andreas Fault from triangulation data. Red curves show posterior distribution of modeled strain rates.

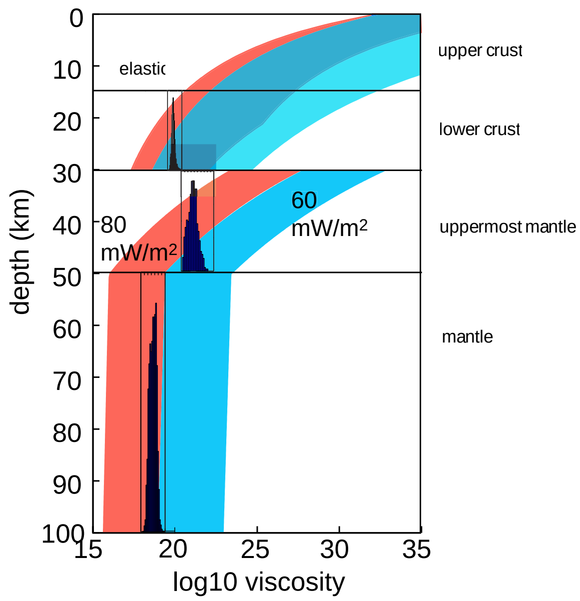


Figure 3: Theoretical viscosity profiles based on laboratory creep measurements. Posterior distributions on viscosity from the three-layered viscoelastic model are superimposed on the theoretical curves.

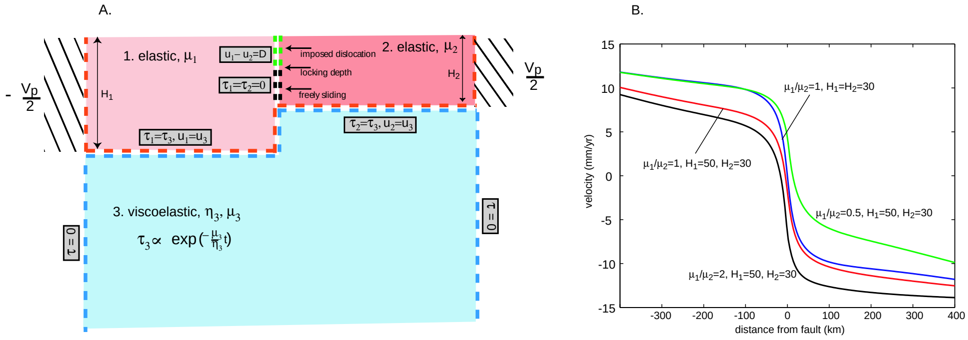

Figure 4: Formulation of antiplane-strain boundary element model. A. Illustration of boundary conditions. B. Resulting surface velocities assuming repeating earthquakes every 200 years and fault slipping 30 mm/yr with viscosity of $10^{19}$ Pa s.

# Reports Published


Hilley, G. E., Burgmann, R., Zhang, P.-Z., and Molnar, P., 2005, Bayesian inference of plastosphere viscosities near the Kunlun Fault, northern Tibet, Geophysical Research Letters, 32(1), doi:10.1029/2004GL021658, L01302.

Hilley, G. E., and J. J. Young, in press, Determining event timing, recurrence, and correlation from paleoseismic excavation data along the central and southern San Andreas Fault, California.

Johnson, K.M., and Segall, P. 2004. Viscoelastic earthquake cycle models with deep stress-driven creep along the San Andreas Fault system, Journal of Geophysical Research, 109, B10403, doi:10.1029/2004JB003096.


# Non-technical Summary

This project improves estimates of earthquake hazard potential in Southern California by formally assimilating geologic, geodetic, seismic, and paleoseismic data into a statistical framework that refines knowledge of the timing and recurrence of ancient earthquakes, slip rates and locking depths of active faults, and rheology of the lithosphere. We have constructed three mechanical models that are being used to invert this data for the parameters of interest. The modeling shows that in order to resolve lithosphere rheology, we must have surface deformation data spanning multiple time periods.